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Effect of Steel Overheat and Casting Speed on the Formation of Rail Steel Ingots

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Abstract

This paper investigates the temperature and speed regime of rail steel casting to reduce ingot defects, such as cracks, non-metallic inclusions, and shrinkage, and improve the quality of steel products. Analytical and experimental approaches were used to determine the effect of casting temperature and mold filling rate on the quality of calm steel ingots. Defects were analyzed and a mathematical model was developed to optimize casting parameters. For the first time, a comprehensive analysis of the dependence of rail steel ingot quality on the parameters of the temperature and speed regime of casting, taking into account the steel grade, was carried out. An optimization parameter is proposed and a methodology is developed for determining the optimal temperature and speed regime for casting steel into ingots using the siphon method, based on the approximation of experimental data. The results of the study make it possible to improve the quality of rail steel ingots by reducing the number of defects, which contributes to resource savings and improved performance properties of metal products. The proposed recommendations can be used at metallurgical enterprises to improve steel casting technology.

KEY WORDS: *steel casting; temperature and speed conditions; rail steel; ingot defects; siphon casting; optimization*

1. Introduction

Rail transport is a key element of the infrastructure of the modern transportation system, providing reliable and efficient transportation of passengers and goods. High quality requirements for rails are driven by the need to ensure their durability, wear resistance and resistance to dynamic loads. One of the critical factors affecting the mechanical properties of rail steel is the temperature and speed regime of ingot casting, which determines the microstructure, level of internal defects and uniformity of chemical composition.

Modern steelmaking plants produce rail steel using various casting technologies, among which considerable attention is paid to controlling the temperature and speed of casting. Failure to comply with the optimal conditions can lead to defects such as central porosity, axial liquation, hot cracks and significant heterogeneity in the ingot structure. This, in turn, adversely affects the mechanical properties of the finished rails, which can lead to premature wear or failure during operation.

This paper investigates the optimization of temperature and speed conditions for pouring rail steel to reduce ingot defects. An approach is proposed that takes into account the peculiarities of heat removal, metal crystallization, and mold filling kinetics. The results obtained can be used to improve the casting process and improve the quality of rails, which is of key importance for the reliability and safety of railway transport.

During steel production, various defects can occur that significantly affect its quality and performance properties, which in turn reduces the reliability of rail transport and increases the risk of accidents, especially when transporting dangerous goods [1]. The most common defects include cracks, delamination, tearing, shrinkage cavities, and non-metallic inclusions. As a result of the literature and statistical analysis, the main causes of these defects were identified and the classification and causes of the main defects were considered [2].

Cracks. Depending on the location and causes of formation, several types of cracks are distinguished: cold (from temperature and phase transformations), hot, longitudinal, edge, transverse, and hot crack grid. Cold cracks occur at low temperatures in a metal with significantly pronounced elastic properties. In carbon steel ingots, phase transformations usually occur at temperatures above 700 °C, when the metal has significant ductility and creep, which prevents stresses from developing. Therefore, in such ingots, under normal conditions, cold cracks are formed only due to temperature stresses.

Of the surface defects, hot cracks, which occur at temperatures close to the crystallization temperature, are the most complex in origin and difficult to prevent. In rectangular ingots, such cracks can be located on their faces and edges (corners). Corner cracks are mostly longitudinal, while cracks on the edges can be both longitudinal and transverse.

The length of hot cracks varies (from 0.1 to 1 m or more). They have a discontinuous and zigzagging (sometimes with oxidized edges) surface. The metal near the cracks is usually decarburized. These features are the main external differences between hot cracks and other types of cracks.

The temperature of the metal being poured has a significant impact on the formation of hot cracks. An increase in temperature usually leads to a decrease in the growth rate of the ingot crust and an increase in the likelihood of local "washouts", which causes an increase in stresses. In addition, the first stage of crust formation (lowering the temperature on its surface) is prolonged, which increases the time of existence of thermal tensile stresses on the ingot surface. These factors lead to the appearance of cracks during the period of filling the lower half of the mold, i.e. at the stage when the metal temperature in it is still quite high

Crack formation is significantly affected by sulfur content in the metal above 0.030-0.035%, which greatly reduces the ductility of steel at high temperatures and gives it the property of red brittleness. The harmful effects of sulfur can be somewhat reduced by increasing the manganese content to maintain a Mn/S ratio of more than 20-25.

Flooding and sagging. During the filling of castings with quiescent steel, especially in the process of siphon casting, oxidized films and crusts are formed on the metal surface, depending on its temperature, chemical composition and rate of flow, which gradually increase and reach significant sizes in the upper part of the casting. Floating non-metallic inclusions are trapped by the crust and contaminate it. If there is a layer of liquid metal (gate) of sufficient width near the walls of the mold, the resulting crust falls into the yield part of the ingot and is removed with it. If the rundown is narrow, the crusts freeze to the solidifying cork part of the ingot and are turned upside down. The incoming metal floods these crusts, and they are either eroded away (in whole or in part) or remain in the ingot. Most often, the crusts are located in the upper half of the ingot, i.e. at the junction of the gating and the gating insert. The shape, size, and location of crusts along the intersection of ingots and billets can vary.

Crusts trapped in the ingot body are very difficult to detect. Even during ingot height quality control, the poured crust may not fall within the cross-section of the controlled temper. Crusting can also affect individual ingots. Oxidized crusts accompanied by large non-metallic inclusions, including complex oxide compounds and refractories, affect the quality of the metal.

To prevent the crust from turning, it is necessary to control the surface of the metal that rises in the mold. If the mold is well lubricated and the pouring speed is normal, the metal should always "move away" from the walls, forming a completely clean, foam-free gating. This is achieved by adjusting the pouring speed to the temperature and the flowing liquid (it should be borne in mind that an increase in the pouring speed and temperature for a number of steel grades can lead to hot cracks in ingots).

Based on the above, a filling mode is chosen (depending on the steel grade, ingot shape and weight, and casting temperature) that fills 1/4, 1/2, 2/3 (or even the entire mold in height) without crusting on the metal surface. Above this level, it is possible to allow the formation of films and crusts while maintaining liquid wound near the walls of the mold.

Pouring metal using floating dry wooden frames prevents the formation of crusts. To observe the casting process by the appearance of the metal surface and to control its speed, one mold on each pallet is left without a frame.

To prevent the formation of a crust on the metal surface in the mold, casting should be carried out under slagging and heat-insulating mixtures, liquid slag, heat-insulating disks, etc.

The removal of the foam is possible by grinding and flame stripping. In most cases, it is not possible to eliminate the influxes.

2. Methodology of the Research

The development of defects in a rail steel ingot, such as shrinkage cavities, porosity, columnar crystallization, segregation, cracks, and others, largely depends on the choice of temperature and speed conditions for casting steel. At the same time, there is no single universal dependence of quality ingots on these parameters, as the casting method and chemical composition of steel can vary significantly depending on the production process [3].

The casting temperature is one of the key parameters that determines the quality of ingots. It affects the development of shrinkage cavities and porosity, the nature of steel crystallization and segregation, the processes of soluble and insoluble impurities, and the formation of cracks and pitting on the ingot surface.

At elevated casting temperatures and the corresponding overheating of steel, the amount of heat transferred per unit area of the ingot's side surface significantly affects the rate of crystallization. Excessive overheating reduces the solidification rate, resulting in the formation of a thin and weak crust that is prone to tearing. In the opposite case, when the heat input is insufficient, the ingot solidifies too quickly, which can cause internal stresses and surface defects. At the same time, the insufficient heat does not compensate for heat loss due to radiation from the exposed surface of the metal, which rises during pouring into the mold.

Optimal temperature parameters of steel casting help minimize surface defects and improve the quality of rail steel. Achieving the required temperature and speed conditions is possible through the use of steel finishing in a ladle furnace [4], which ensures precise control of the metal temperature and its homogeneity before casting. This can significantly reduce the level of defects and improve the performance of rails, which is critical for the reliability of the railway infrastructure [5].

For the studies [6, 7] conducted on steels 20, St3, 14KhGS and 19G, which are poured into ingots weighing 8.6, 9.6 and 12.8 tons by siphoning, the optimal $q_{cast} = 160 \div 181$ kW/m^2.

The calculation of the temperature-rate regime for casting calm steels PT70sp and 70G for ingots H=2200 mm and

P/*S*=6 based on these values indicates that the actual casting parameters correspond to the specified temperature-rate regime only at high overheating of the steel.

The actual pouring speed and pallet filling time, although within the limits of the established TI for a given enterprise, are practically independent of the steel superheat temperature, and its change is random. However, in any case, the pallet filling time must be varied depending on the temperature of the steel at the casting site.

As emphasized above, cracks and foams are typical defects caused by non-compliance with the temperature and speed regime of casting. Therefore, an optimization technique should be applied to develop a casting regime for quiescent steel of various grades. The optimized parameter is the fraction $\Delta T / \tau \sim \Delta T \times w$ (τ - is the time of filling the ingot body), and its optimal value will correspond to the simultaneous minimization of cracks and films.

3. Optimization of the Temperature and Speed of the Casting Process

Optimization of the temperature and speed regime of steel casting helps to reduce these defects, which improves the durability of rails, reduces maintenance costs, and minimizes environmental risks associated with the transport accidents discussed in [1]. To optimize the $\Delta T / \tau$ parameter, we used the melt data sheets of the calm steel grades K63, PT70sp, 70G, and 09G2S. This value for steel grade K63 was found by solving the system of quadratic equations (1) obtained by approximating the points.

$$\begin{cases} 0.0119x^2 - 0.4191x + 3.7921 - y = 0; \\ 0.0051x^2 - 0.0909x + 0.4711 - y = 0. \end{cases} \tag{1}$$

Similarly, we find the optimal value for other steel grades.

During the period under consideration, no cracks or films were observed on ingots of 09G2S steel, which indicates the correctness of the temperature and speed regime of its casting. The optimal values of the $\Delta T / \tau$ parameter for other steel grades are shown in Table.

Table

Optimal values of the $\Delta T / \tau$ parameter for the brands under study

Steel grade	K63	PT70sp	70G
The value of the parameter $\Delta T / \tau$	14,44	8,94	8,92

The optimal values of the $\Delta T / \tau$ parameter can be used to calculate the pouring rate (time to fill the ingot body) at certain steel temperatures in the ladle and its holding time.

According to the current TI at the enterprise, the temperature loss in the ladle is 1 °C per minute. According to the results of the calculation according to the methodology [8], a temperature drop of 1.3-2.5°C/min was obtained, depending on the ladle stability. Given that the temperature drop in the ladle averages 1°C/min, the time and rate of filling the ingot body are calculated using the following formulas:

$$\tau_t = \frac{t_e - t_b - \tau_{holding}}{\Delta T / \tau}, \text{ min}, \tag{2}$$

$$w_t = 2.2 \cdot \frac{\Delta T / \tau}{t_e - t_b - \tau_{holding}}, \text{ m/min}, \tag{3}$$

where t_b – the initial time of the process, min; t_e – the final time of the process; $\tau_{holding}$ – the holding time of steel in the ladle, min.

Using these formulas, we calculated the rational temperature and speed regimes for casting rail steel grades for holding the metal in the ladle before casting from 5 to 20 minutes.

4. Conclusions

A detailed classification of the most typical defects in the production of calm steel grades was made, indicating the causes of their occurrence and international experience in preventing and eliminating them. A temperature and speed regime for steel casting was developed and tested, taking into account the steel grade and the holding time of the metal in the steel ladle. The results of the pilot melts showed a 57.45% reduction in the number of rejects in the production of calm steel grades.

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